Designing a Narrowband 28 GHz Bandpass Filter for 5G Applications

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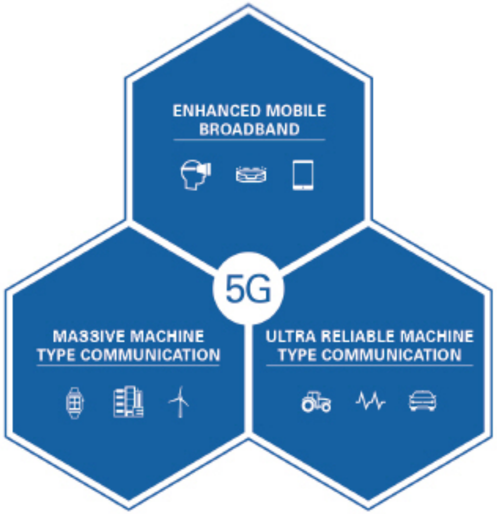
Agenda

- 5G Applications and Filter Requirements
- 5G Challenges: Performance, Cost and Manufacturing
- Design Approaches and Filter Specifications
- Designing a Physically Realizable 5G Filter

5G Applications and Filter Requirements

Initial 5G (NR) Focus, Deployment and Applications

- enhanced Mobile Broad Band (eMBB)
- massive Machine Type Communication (mMTC)
- Ultra Reliable and Low Latency Communication (URLLC)



Entering the practical design phase – developing specs from established standards and timelines

- 3GPP Rel. 15 –
  - Introduces non-standalone (NSA) 5G NR bands for faster data rate
  - NSA uses LTE anchor band for control
- **Benefit:** solidifies target bands, carrier aggregation, waveforms, modulations and sub-carrier spacing providing critical information to chip and handset manufacturers
- **Cost:** RF complexity supporting dual 4G LTE and 5G connectivity
  - danger of harmonics from handset transmitting LTE anchor falling into 5G receiver bands (3.3-3.8GHz)
  - requiring filter solutions (low insertion loss, selectivity, complexity)

5G Devices/Applications

- Handsets
  - Will continue to use SAW, BAW and FBAR (FR1, < 6 GHz)
  - Single crystal BAW (Akoustis) are being introduced for higher frequencies, targeting 5GHz Wi-Fi routers

- Small cells and micro cells
  - High channel counts in these relatively small-sized base stations will require small-form-factor filter solutions

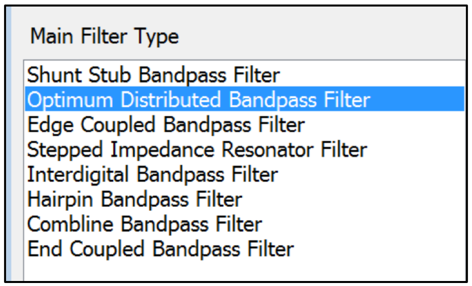
- mmWave Backhaul
  - Intermediate link between the core network and base stations serving a given area.
  - Filter requirements: expect challenging cost and volume concerns

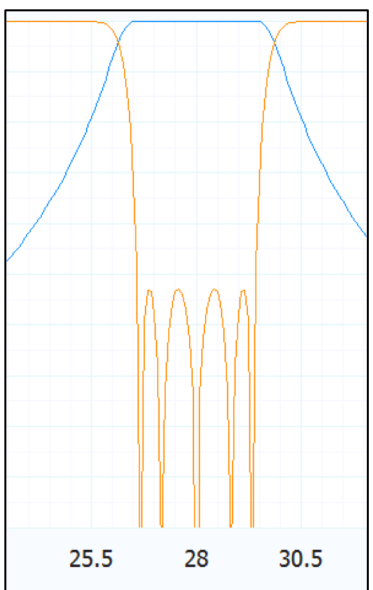
5G Challenges: Performance, Cost and Manufacturing

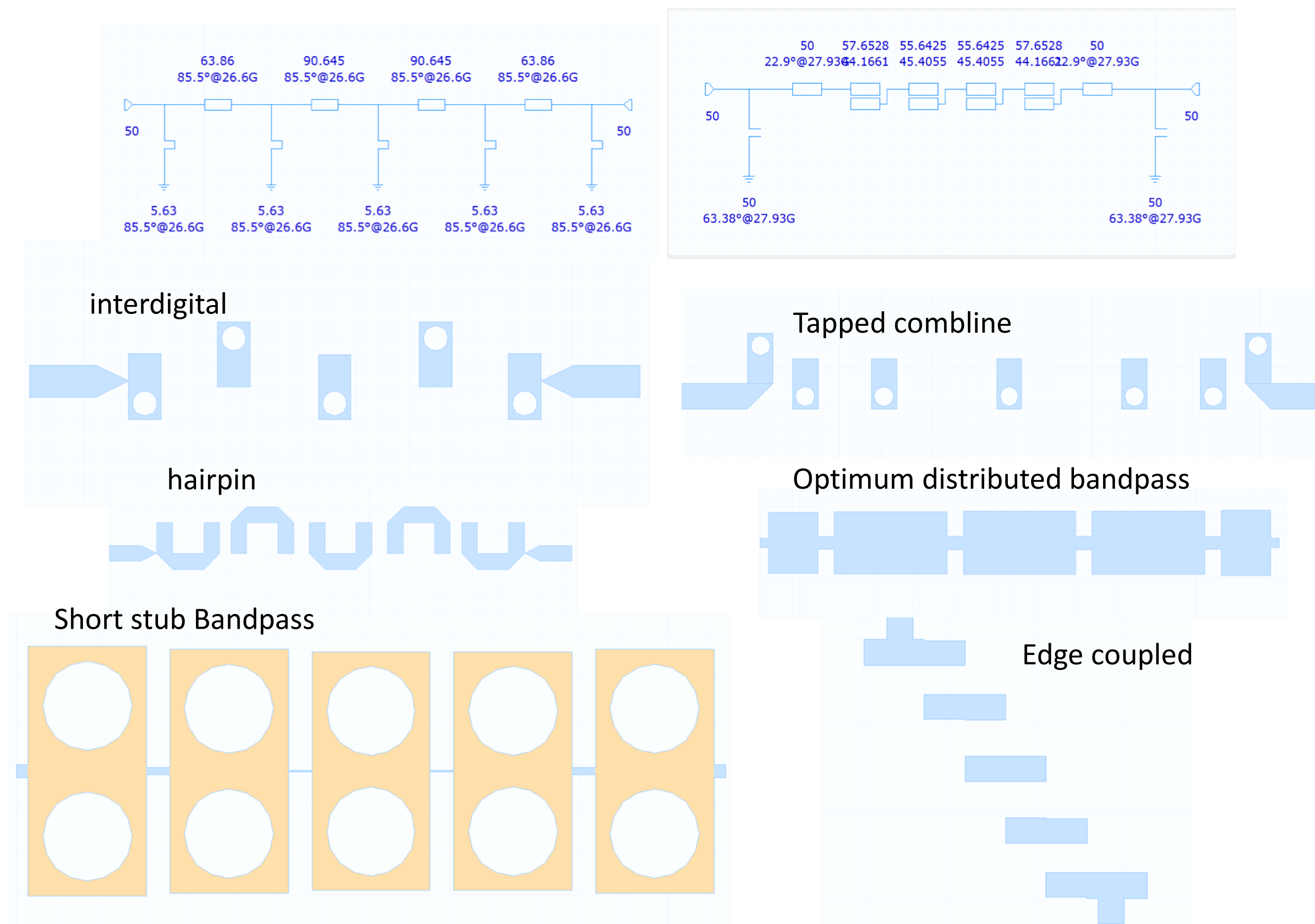
Filter Considerations: Initial Design

- Well-established mathematics define filter responses (including narrow bandpass), which can be produced exactly with ideal LC elements through commercial synthesis tools.
- For a mm-wave design, we will implement a distributed network, **transmission line** and **waveguide cavity** (not an LC network).
- The synthesis tools such as iFilter from NI AWR design software can perform the math to produce exact, ideal LC filters and certain distributed designs (edge-coupled, hairpin, interdigital, combline, etc.) based on ideal distributed models (microstrip, stripline).
- Synthesis results do not necessarily produce realizable or accurate physical designs.

Filter Considerations: Design to Build



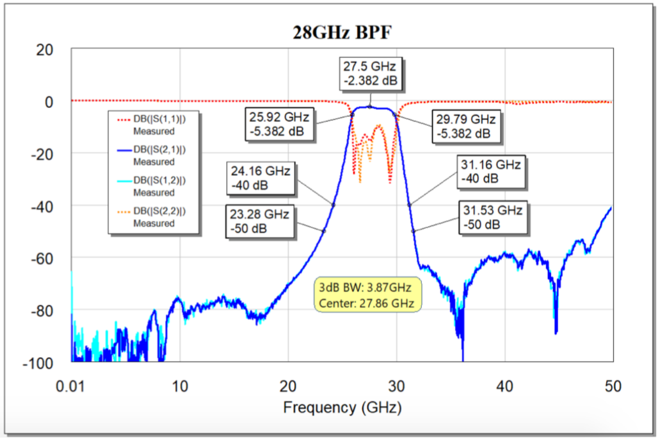


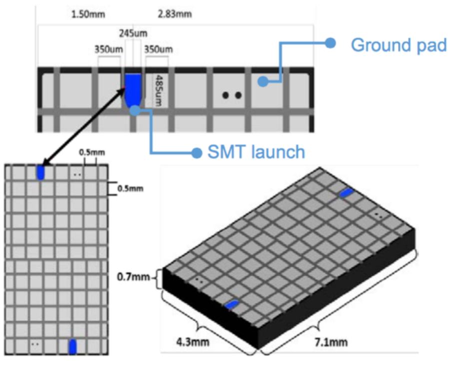


5G Manufacturing Breakthroughs

3D GLASS SOLUTIONS

- **Wafer-based (Si or GaAs)**
  - **RF-MEMS** cavity resonators (20 to 100 GHz)
  - Integrated Passive Devices (IPD)
- **3D Printing**
  - Materials and processes
  - Surface roughness
  - Tolerances (near-net-shape vs near-net-size)
- **Etched LTCC**
  - Etched features rather than screen printed
  - Tolerances (shrinkage)
- **APEX® Glass (3D Glass)**
  - Photosensitive glass-ceramic material
  - Anisotropic 3D features

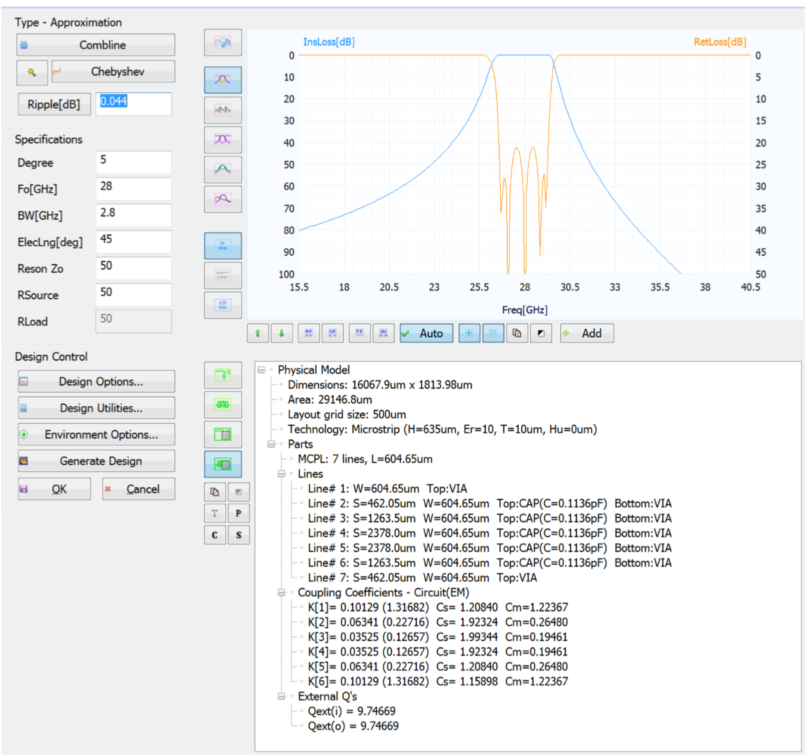


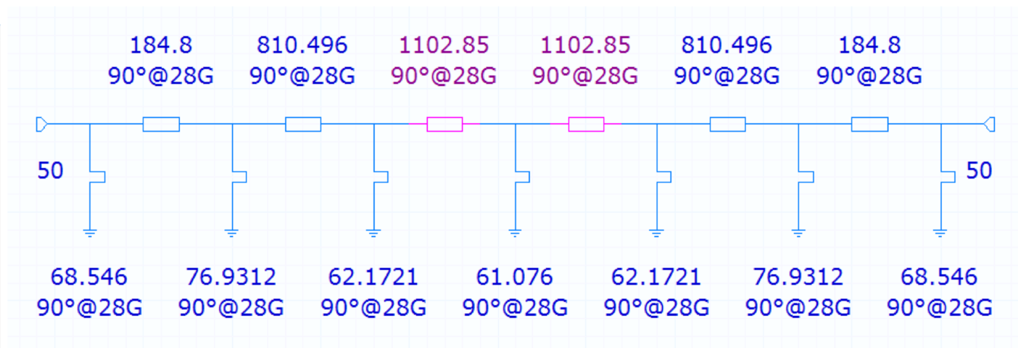


Design Approaches and Filter Specifications

Design by Synthesis

Good for initial filter design but ability to produce a physically realizable filter as a standalone tool is limited.





Method Developed by D. Swanson

- Use **Dishal's method** to identify narrow-band, lumped-element, or distributed bandpass filter parameters using **three fundamental variables**:
    1. the synchronous tuning frequency of each resonator, f_0
    2. the couplings between adjacent resonators, ***Kr, r+1;***
    3. and the singly loaded or external Q of the first and last resonators, ***Qex***
- Parametric study of resonators and coupling using **EM Simulation** of distributed and waveguide filter components (i.e. open stubs)
- **Port Tuning** - internal ports provide connection points for tuning ideal elements (components) located in strategic locations.

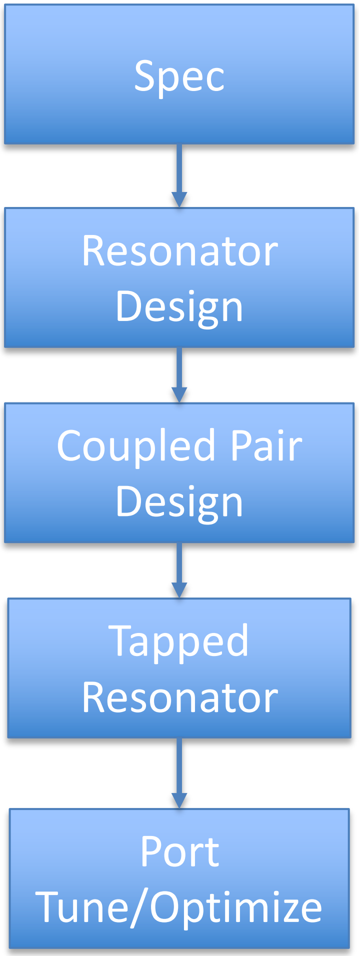
Design by Optimization

- General purpose optimizers aren't efficient for filters
- Whereas filters have well defined optimal response with mathematical foundation, which can be utilized.
- For a lossless Chebyshev filter, optimal response is equal ripple insertion and return loss in passband
- If we can consistently find this equal ripple, we can design filter using optimization
- An equal ripple in passband is still the goal even with cross-coupling added *(not used in our design)*
- We can design using accurate network theory or EM based models
- This optimizer is available as an add-on tool to NI AWR Design Environment from Dan Swanson

Designing a Physically Realizable 5G Filter

Specific Design Steps

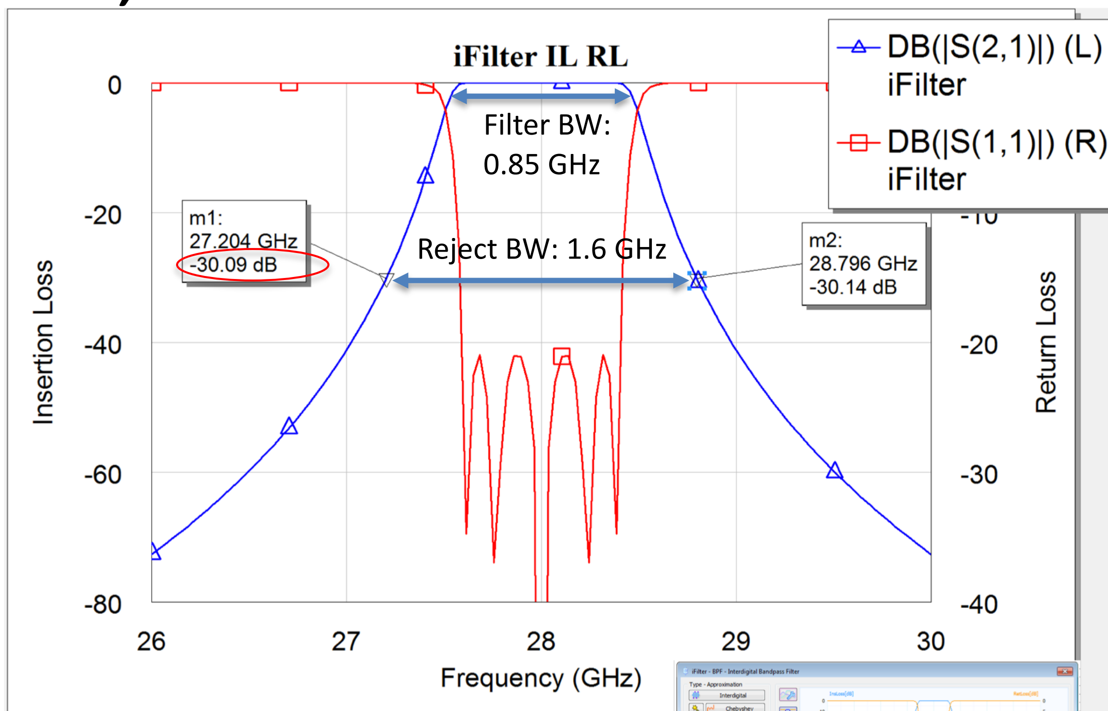
- Specify BW, stopband rejection and determine order of filter
- Build a EM model of the proposed resonator:
  - Compute available unloaded Q and length for desired resonant frequency
  - Estimate insertion loss
- Build K_{ij} design curves from coupled resonator pair
- Build Q_{ex} design curves from tapped resonator
- Build a model of complete filter and apply port tuning to refine the filter dimensions through optimization
- Perform final simulation of complete filter
  - Verify insertion loss in passband
  - Verify rejection in stopbands



Narrowband Bandpass Filter for 5G

- Filter Type: **Interdigital**
- Structure: **Single in-line cavity**
- Electrical requirements
  - Center Frequency: **28 GHz**
  - Bandwidth: ~3% (850 MHz) (3GPP allocated)
  - Max. Insertion loss (in-band): **TBD**
  - In-band Return Loss: **20 dB**
  - Rejection in Stop-band: 30 db ($f_0 \pm$ 800 MHz)
  - Filter Order, N (no. of resonators): **TBD**
- Return loss/Ripple:
  - Ripple (dB) = mismatch loss (dB) = $10*\log[1-((VSWR-1)/(VSWR+1))^2]$
  - Example: VSWR of 1.22 (RL=20.0 dB) translates to **.044 dB ripple**

Estimate Filter Order, N



Filter Order

$$N > \frac{Rejection\,(\mathrm{dB}) + RtnLoss\,(\mathrm{dB}) + 6}{20\log_{10}(S + \sqrt{S^2 - 1})}$$

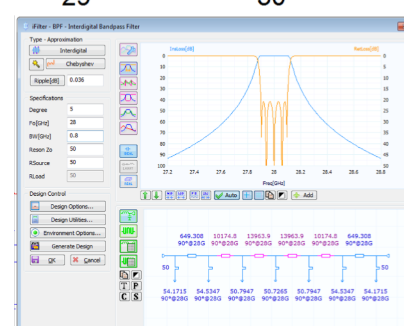
$$Rejection = \text{Stopband Insertion Loss}$$

$$RtnLoss = \text{Passband Return Loss}$$

$$S = \frac{\text{Reject Bandwidth}}{\text{Filter Bandwidth}}$$

Rejection: 30 dB
Reject Bandwidth: 1.6 GHz
Filter bandwidth: 0.85 GHz
Return loss: 20 dB
∴ N > 4.89. (set N to 5)

Ifilter used to generate initial idealized 5th order interdigital filter schematic and gain sense of filter response



Ideal Lowpass Chebyshev Response

Chebyshev Lowpass Prototype: 0.044 dB ripple, 20 dB return loss, 1.22 VSWR

N	g_0	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	$\Sigma g_1 - g_N$
2	1.0000	0.6682	0.5462	1.2222								1.2144
3	1.0000	0.8534	1.1039	0.8534	1.0000							2.8144
4	1.0000	0.9332	1.2923	1.5795	0.7636	1.2222						4.5727
5	1.0000	0.9732	1.3723	1.8032	1.3723	0.9732	1.0000					6.4989

From ripple and order, we obtain the normalized lowpass filter element values (***g**$_i$*) to derive:

- $K_{i,j}$ = coupling coefficient
- Qex = external Q

*The graphs and equations in **Matthaei, Young, and Jones** are very useful for estimating an ideal, symmetrical Chebyshev response.*

And insertion loss:

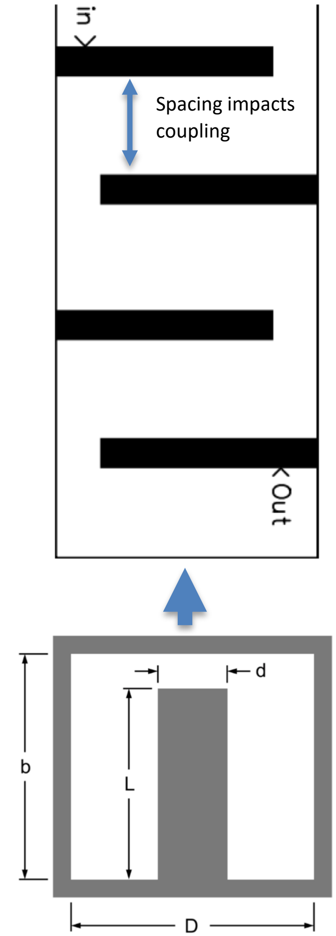
$$Loss(f_0) = \frac{4.343 f_0}{\Delta f Q_u} \sum_{i=1}^{N} g_i \text{ (dB)},$$

Δf: is the equal ripple bandwidth of the filter

Q_u: is the expected average unloaded Q for the resonators

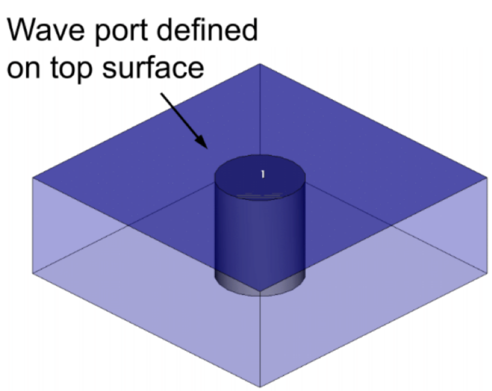
Some Initial Design Details

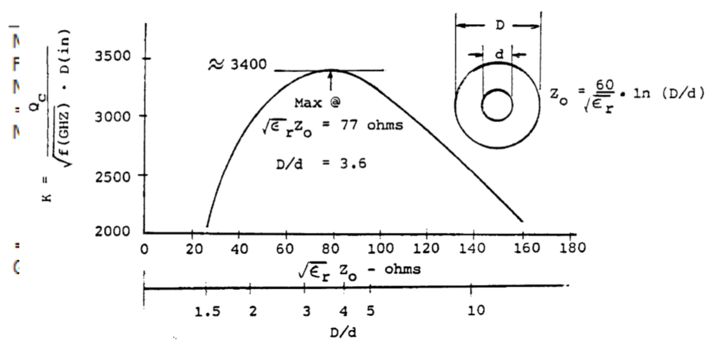
- Use Interdigital filter for its performance characteristics
  - The coupling between resonators is controlled by their separation
    Interdigitated resonators positioned with alternating open ends
  - Each resonator is ~ λ/4 long, physically shortened to accommodate the tuning screw
  - We will use taps on the input and output resonators to make input and output connections
- The width of the cavity (b) should be λ/4 at the operating frequency.
- The impact of these dimensions are interrelated, making empirical design of a filter difficult (and frustrating)
- **Port Tuning** and optimization will be used to address the final design details .

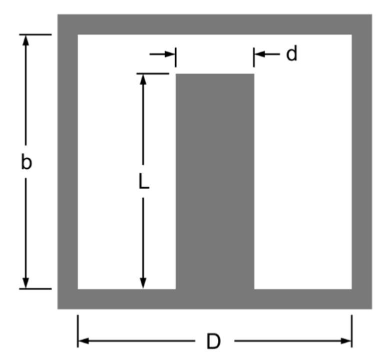


Resonator Design: Z_0

- For a coaxial resonator there is an optimum impedance, around 77 ohms, for unloaded Q.
- In this case the geometry had to be optimized for input / output tapping and we did not achieve optimum Qu.
- Tline approximates: Zo ~ 46 ohms
  - (EM could be used as a 2D cross-section solver to determine Z_0)
- Resonator impedances will be kept fixed,
  i.e. – no changes to post dimensions





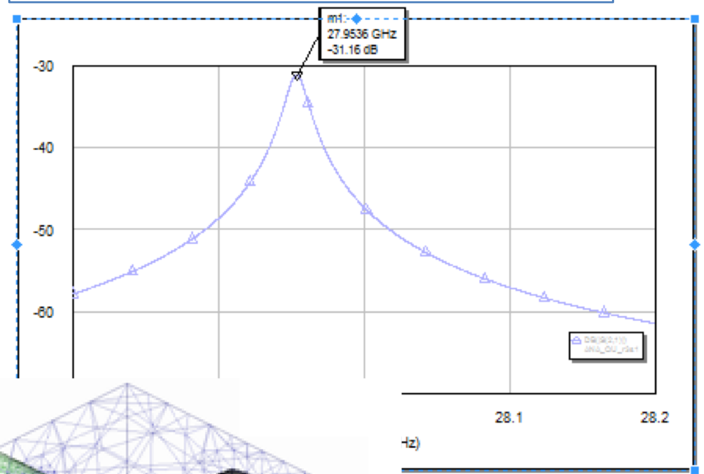


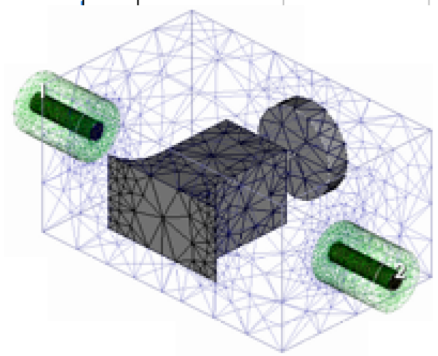
Optimal Z_0 is approximately 77 Ω
Optimal d/D is approximately 0.33
Electrical length is typically 30° to 60°

Simulate Resonant Frequency and Q_u

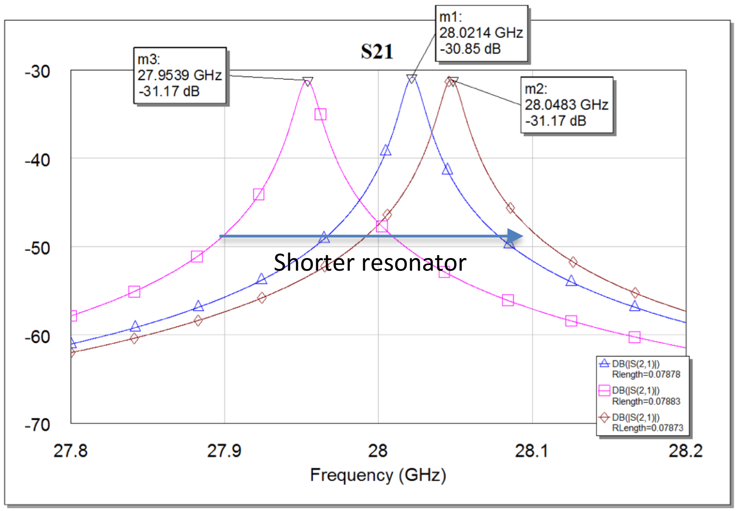
- The passband insertion loss of the narrowband filter is inversely related to the unloaded Q of the individual resonators
- Unloaded Q is proportional to a dominant resonator dimension and is likely sensitive to manufacturing processes as well.
- EM analysis can be used to determine the resonant frequency and unloaded Q
- For any given resonator geometry, the **unloaded Q** can be calculated from time delay at resonance using a loosely coupled 2-port EM measurement

$$Q_u = \pi f_0 \, t_d \frac{10^{IL(dB)/20}}{10^{IL(dB)/20} - 1}.$$

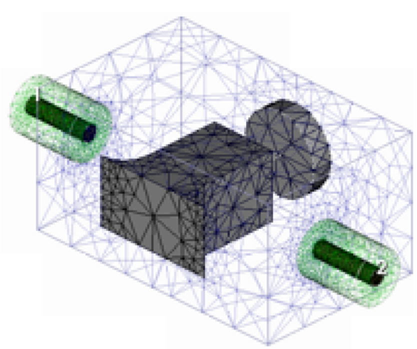




EM Analysis: Resonator Parametric Study



R length	F_0 (GHz)	Qu
0.07883”	27.9535	1975.2
0.07878”	28.022	2040.6
0.07773”	28.043	1978.1



EM model of cavity post resonator, loosely coupled to coaxial I/O ports

Unloaded Q as a function of post and cavity dimensions (L), calculated from time delay at resonance using:

$$Q_u = \pi f_0 t_d \frac{10^{IL(dB)/20}}{10^{IL(dB)/20} - 1}.$$

Insertion Loss from Q_u

- Estimated insertion loss is ~0.25 dB
- Need some information on manufacturing process (plating details) for EM simulation. Our design used **80% of ideal conductivity** as a starting point
- Use measured data from filters to adjust future model conductivity information in the future
- The quality of **silver plating is very process dependent**, varying across different vendors and even different days.
- **Yield Analysis** and optimization via EM simulation can be implemented to mitigate problem and improve yields.

Frequency (GHz)	DB(|Eqn(LOSS)|) Output Equations 1	|Eqn(DELAY)| (ns) Output Equations 1	|Eqn(QU)| Output Equations 1
27.9533	29.874	21.849	1973.3
27.9534	29.873	21.864	1974.7
27.9535	29.873	21.87	1975.2
27.9536	29.873	21.868	1975.1
27.9537	29.874	21.858	1974.2
27.9538	29.875	21.84	1972.5

$$Q_u = \pi f_0 \, t_d \frac{10^{IL(dB)/20}}{10^{IL(dB)/20} - 1}.$$

Estimate mid-band filter loss using the expected average unloaded Q for the resonators

$$Loss(f_0) = \frac{4.343 f_0}{\Delta f \, Q_u} \sum_{i=1}^{N} g_i \text{ (dB)},$$

where Δf is the equal ripple bandwidth

Calculate K, Q from Lowpass Response

- Resonator separation for inter-resonator coupling
- Tap height for external Q

Chebyshev Lowpass Prototype: 0.044 dB ripple, 20 dB return loss, 1.22 VSWR

N	g_0	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	$\Sigma g_1 - g_N$
2	1.0000	0.6682	0.5462	1.2222								1.2144
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5	1.0000	0.9732	1.3723	1.8032	1.3723	0.9732	1.0000					6.4989

$$Q_{ex} = \frac{f_0 \cdot g_0 \cdot g_1}{f_2 - f_1} = \frac{g_0 \cdot g_1}{BW}$$

$$K_{ij} = \frac{(f_2 - f_1)}{f_0\sqrt{g_i \cdot g_j}} = \frac{BW}{\sqrt{g_i \cdot g_j}}$$

$$f_0 = \frac{f_1 + f_2}{2} \qquad BW = \frac{f_2 - f_1}{f_0}$$

f_1 = bandpass filter lower equal ripple frequency

f_2 = bandpass filter upper equal ripple frequency

f_0 = bandpass filter center frequency

BW = percentage bandwidth

g_i = prototype element value for element i

Note: Equations assume Qu is infinite.

$$Q_{ex} = \frac{28GHz(1.0 \cdot 0.9732)}{0.850GHz} = 32.05$$

$$K_{1,2} = \frac{0.03}{\sqrt{.9732 \cdot 1.3723}} = 0.02596 \qquad K_{3,4} = \frac{0.03}{\sqrt{1.8032 \cdot 1.3723}} = 0.01907$$

$$K_{2,3} = \frac{0.03}{\sqrt{1.3723 \cdot 1.8032}} = 0.01907 \qquad K_{4,5} = \frac{0.03}{\sqrt{1.3723 \cdot .9732}} = 0.02596$$

Inter-Resonator Coupling

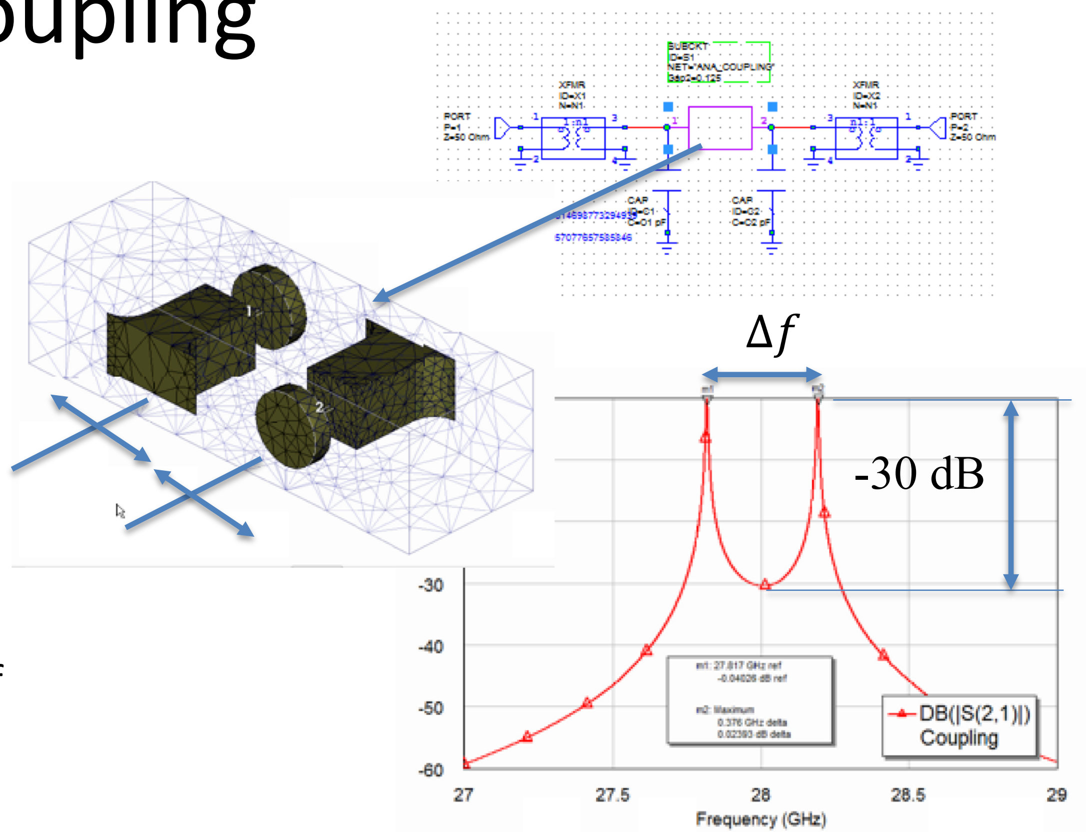
- building K_{ij} design curves

- Two identical resonators (@ f_0) are enclosed in waveguide cavity, loosely coupled to I/O ports

- Coupling between resonators results in a displacement **Δf** of the resonance frequencies.

- **Δf** is the **coupling bandwidth**. The resonate frequency lies at the center of the two peaks

- If the coupling bandwidth is divided by the ripple bandwidth (BW) of the filter, we get the **normalized coupling coefficient: M12 = Δf/BW = K_{ij} f_o**

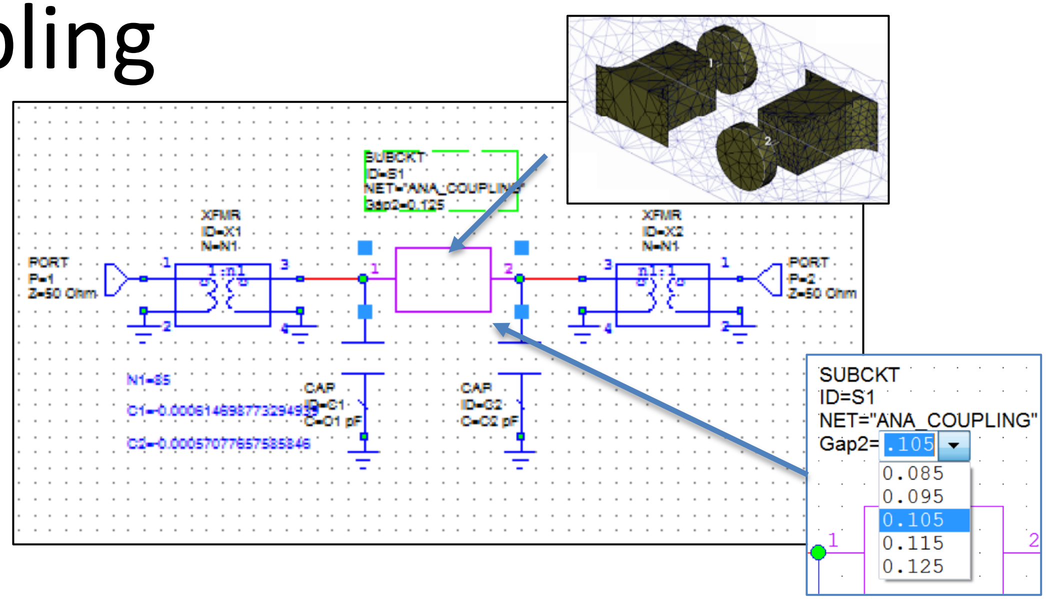


Note: Loosely coupled port sniffers - Port distance to resonator will influence depth of the valley between peaks. It should kept below approximately -30 dB in order to minimize the influence of in- and output connections on the coupling measurement.

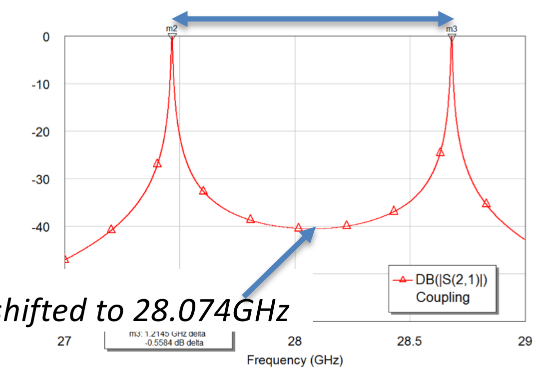
Inter-Resonator Coupling

- building K_{ij} design curves

- EM model embedded in circuit schematic for port tuning
- Loose coupling set by adjusting N1 in transformers X1 and X2.
- Port tuning can be used to address shift in resonant frequency

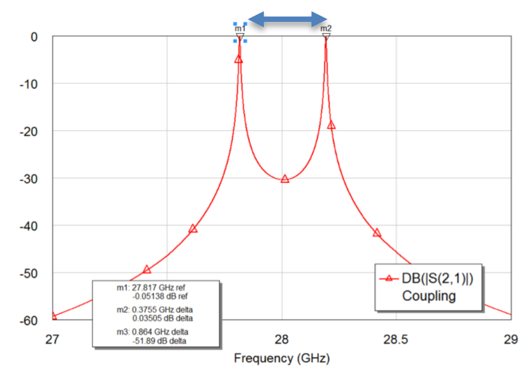


$\Delta f: 1.215\ GHz,$
$spacing = .085''$



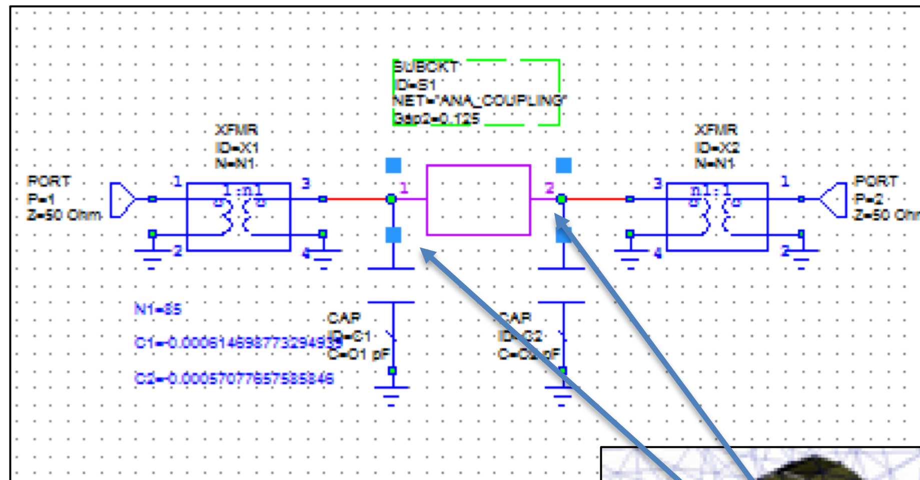
fo shifted to 28.074GHz

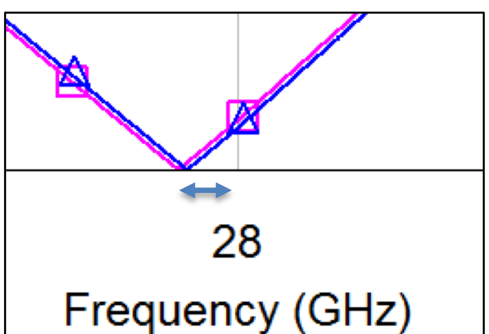
$\Delta f: 0.38\ GHz,$
$spacing = .125''$



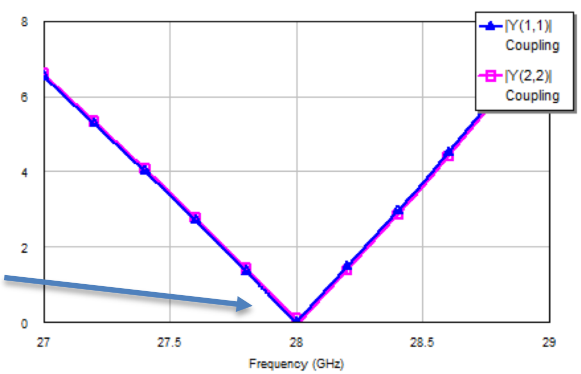
Port Tuning the Coupled Resonators

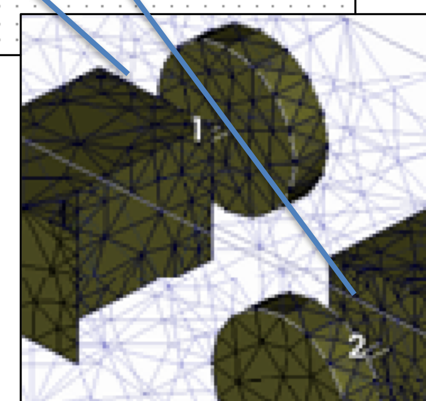
- Lumped ports are attached to both between the resonator and tuning screw for port tuning resonators
- Cap values (c1, c2) are adjusted to “zero out” the reflected input/output admittance at 28 GHz using optimizer to simultaneous resonance for each spacing





fo shift is addressed through tuning c1, c2 values using optimization





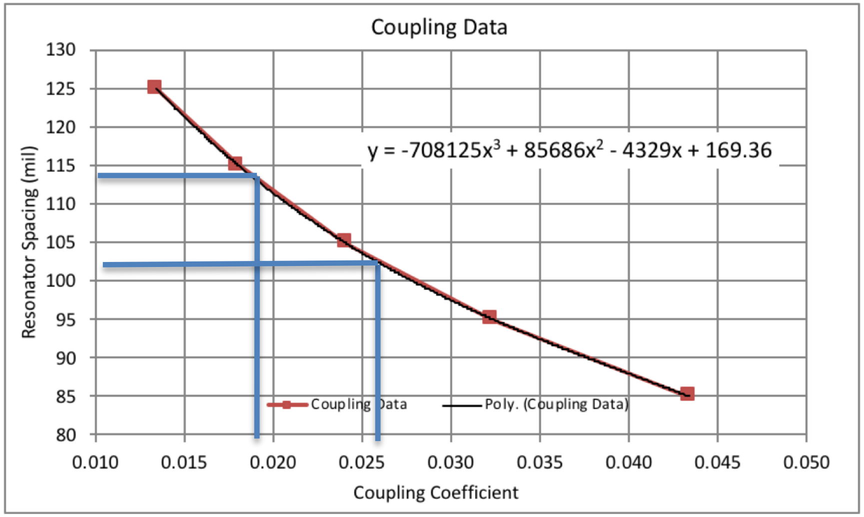
K_{ij} Curves from Parametric EM Analysis

From K_{ij} calculations:
$[K_{1,2}],[K_{4,5}] = 0.02596$
$[K_{2,3}],[K_{3,4}] = 0.01907$

Coupling bandwidth [1,2][4,5] = 726 MHz
Coupling bandwidth [2,3][3,4] = 534 MHz
(= K_{ij} x 28GHz)

From EM analysis: simulated edge-to-edge resonator separation (add 0.050" for center to center spacing):

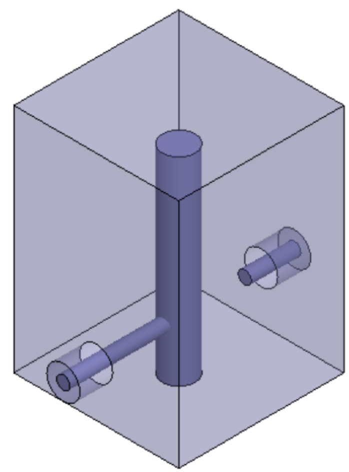
1, 2: 0.102
2, 3: 0.114
3, 4: 0.114
4, 5: 0.102

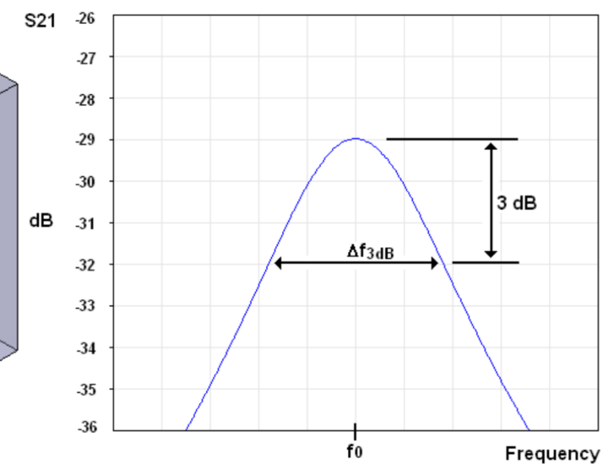


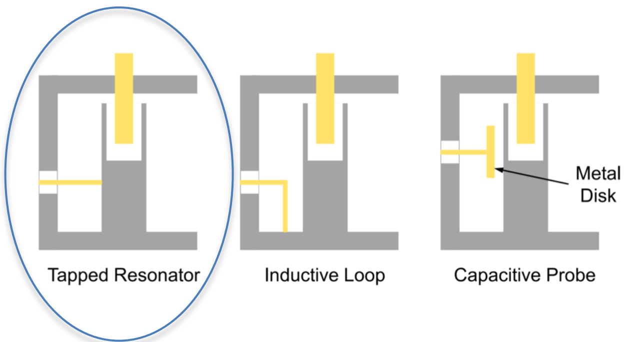
External Coupling

- building Q_{ex} design curves

- External couplings provide filter I/O ports and are expressed by their external Q's.
- The resonator is coupled by a tapped I/O port (to the left).
- Could also be coupled by a non touching capacitive disc, a loop or similar (below).







A loosely coupled "sniffer" port (to the right), supports transmission measurement, Negligible impact if resonance peak is kept below 25 to 30 dB.

The external coupling is found by measuring the 3 dB bandwidth of the resonance curve - denoted Δf3dB.

The external Q is:
Qext = Qloaded = f0 / Δf3dB

Note: It is also possible to determine the external Q by measuring the group delay of S11

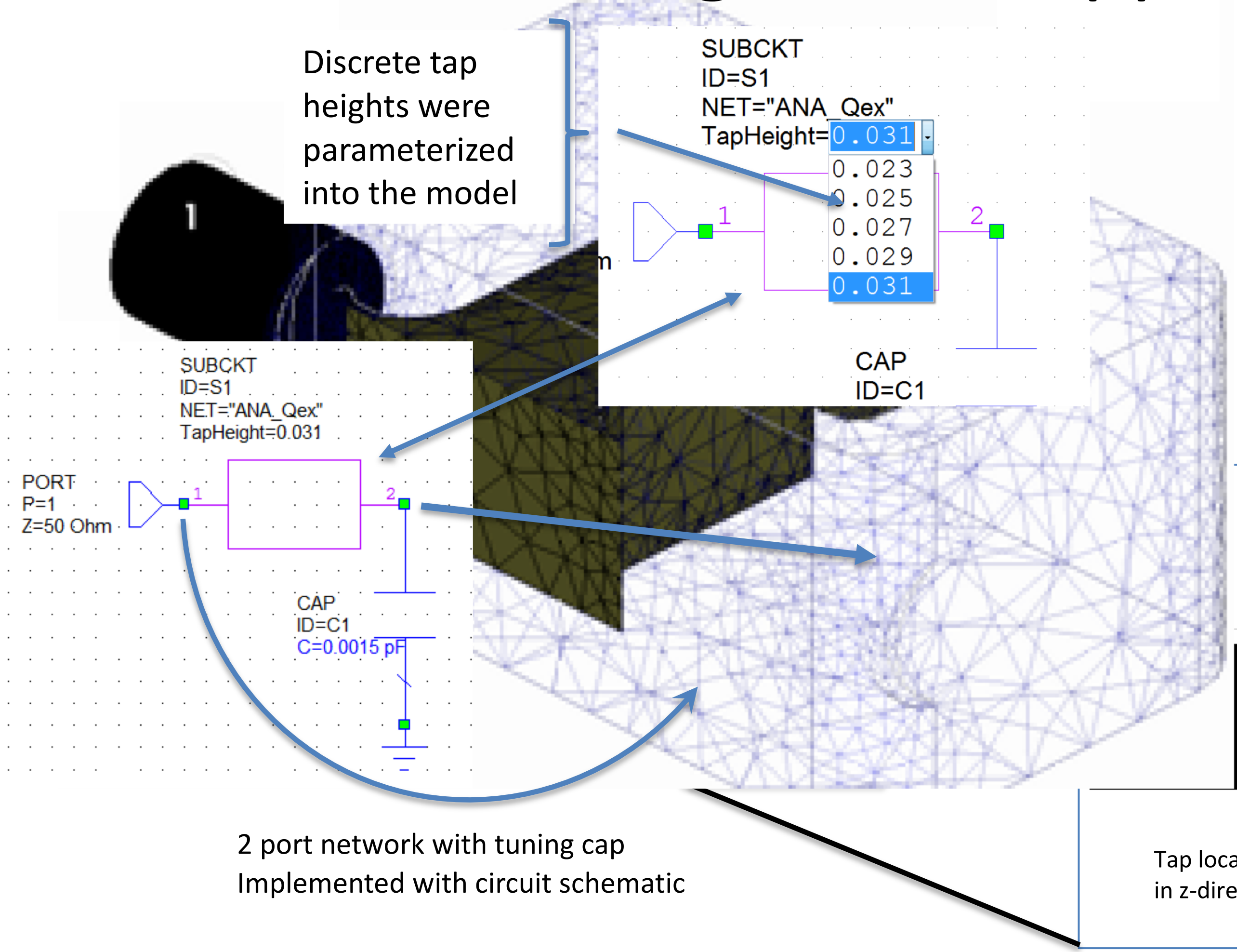
Parametric Modeling of the Tapped Resonator

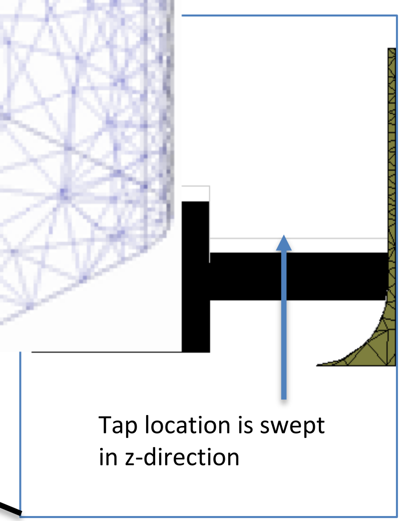
Remember our Q_{ex} Goal:
Find the tap height to achieve Q_{ex} for desired filter response

$$Q_{ex} = \frac{f_0 \cdot g_0 \cdot g_1}{f_2 - f_1} = \frac{g_0 \cdot g_1}{BW}$$

$$Q_{ex} = \frac{1 \cdot 0.9732}{0.03}$$

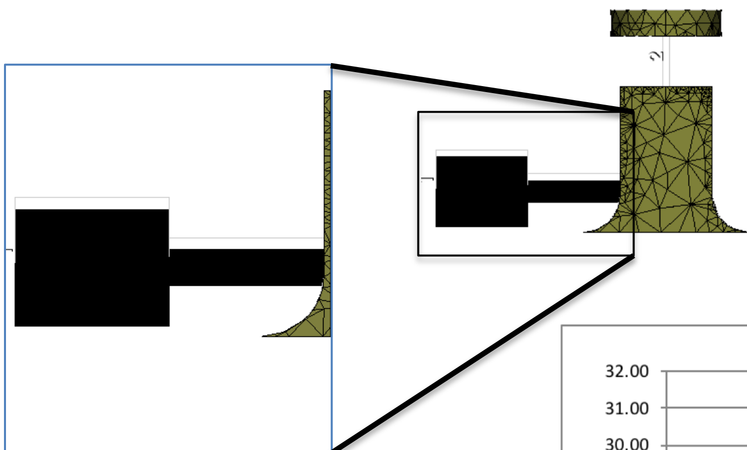
$$\boxed{= 32.4}$$



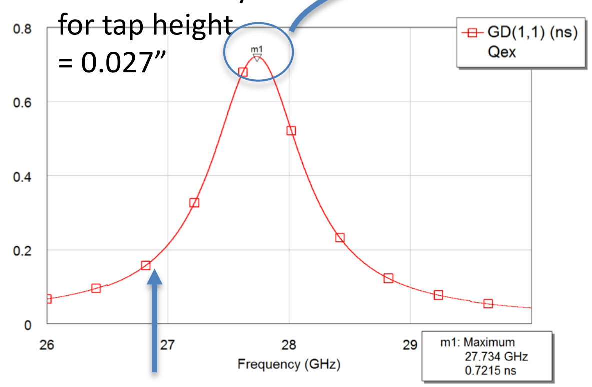


External Coupling

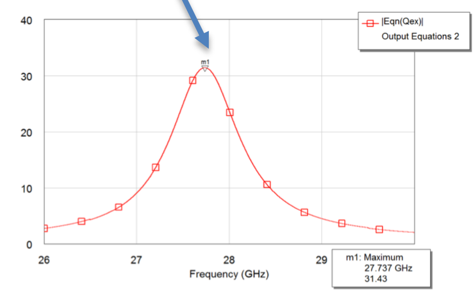
- building Q_{ex} design curves



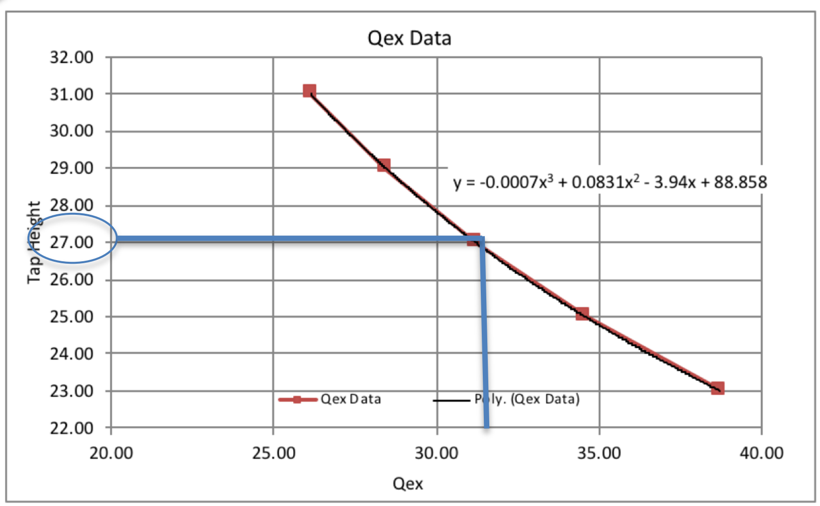
Simulated reflected delay for tap height = 0.027”



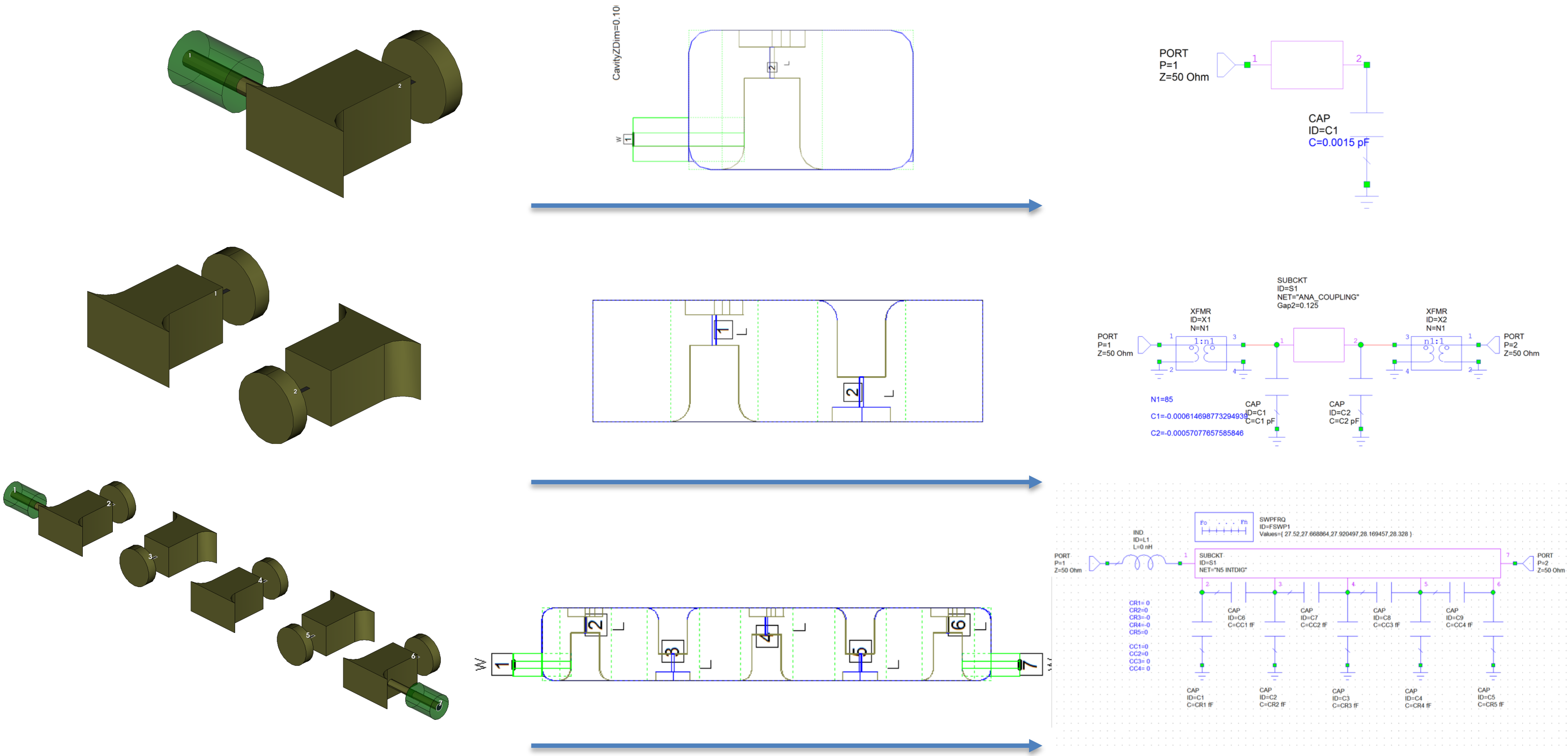
$$Q_{ex} = \frac{2 \cdot \pi \cdot f(GHz) \cdot t_d\,(ns)}{4} = \frac{2 \cdot \pi \cdot 27.734 \cdot 0.7215}{4} = 31.43$$



Resulting Qex vs. tap height based on parameterized swept EM analysis of reflected time delay

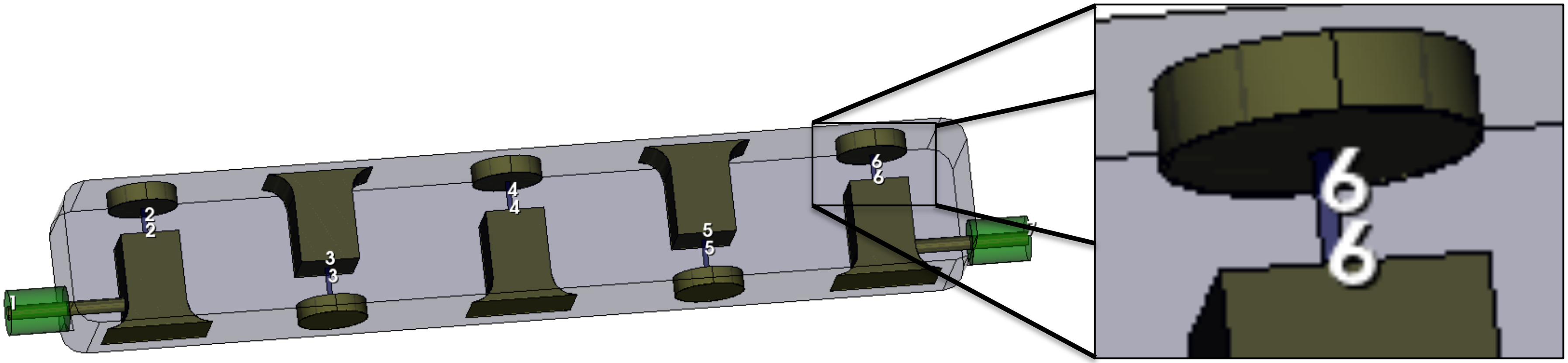


Circuit/EM Hierarchy and Parameterization



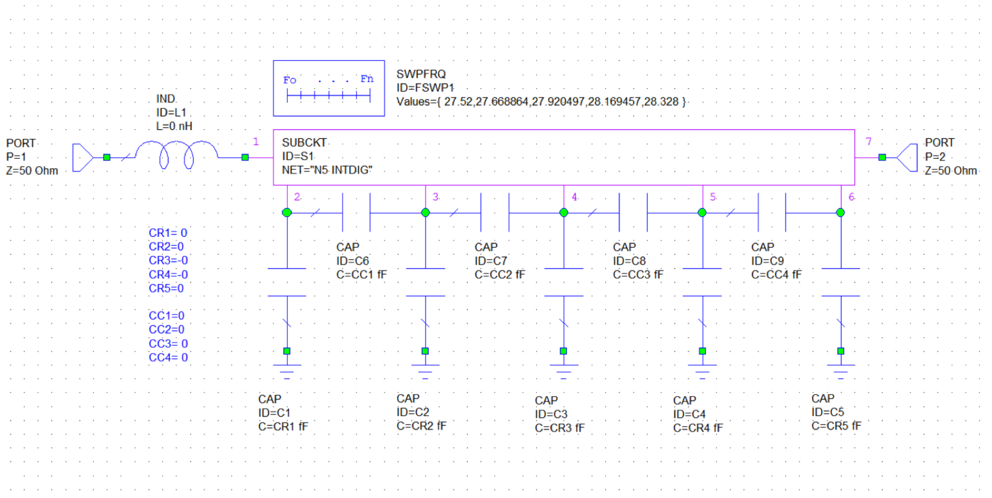
Port Tuning

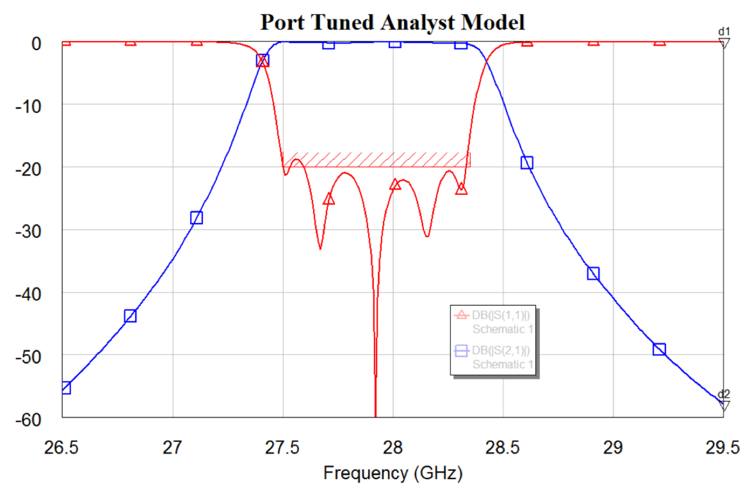
- EM optimization is not practical
  - Simulation run times on the order of minutes or tens of minutes
- Adding a port at each resonator allows us to tune resonant frequency and coupling
- Ports are "loaded" with tunable shunt capacitances in circuit simulator.
  - Series capacitances between resonators node to diagnosis and adjust spacing



Port Tuning

- With a 50 ohm port loading each resonator, EM simulation captures raw coupling between resonators.
- We then compute the filter S-parameters in the circuit simulator.
- The circuit simulator can successfully interpolate between a small number of EM data points.
- Also works for more complex filters such as diplexers and multiplexers.

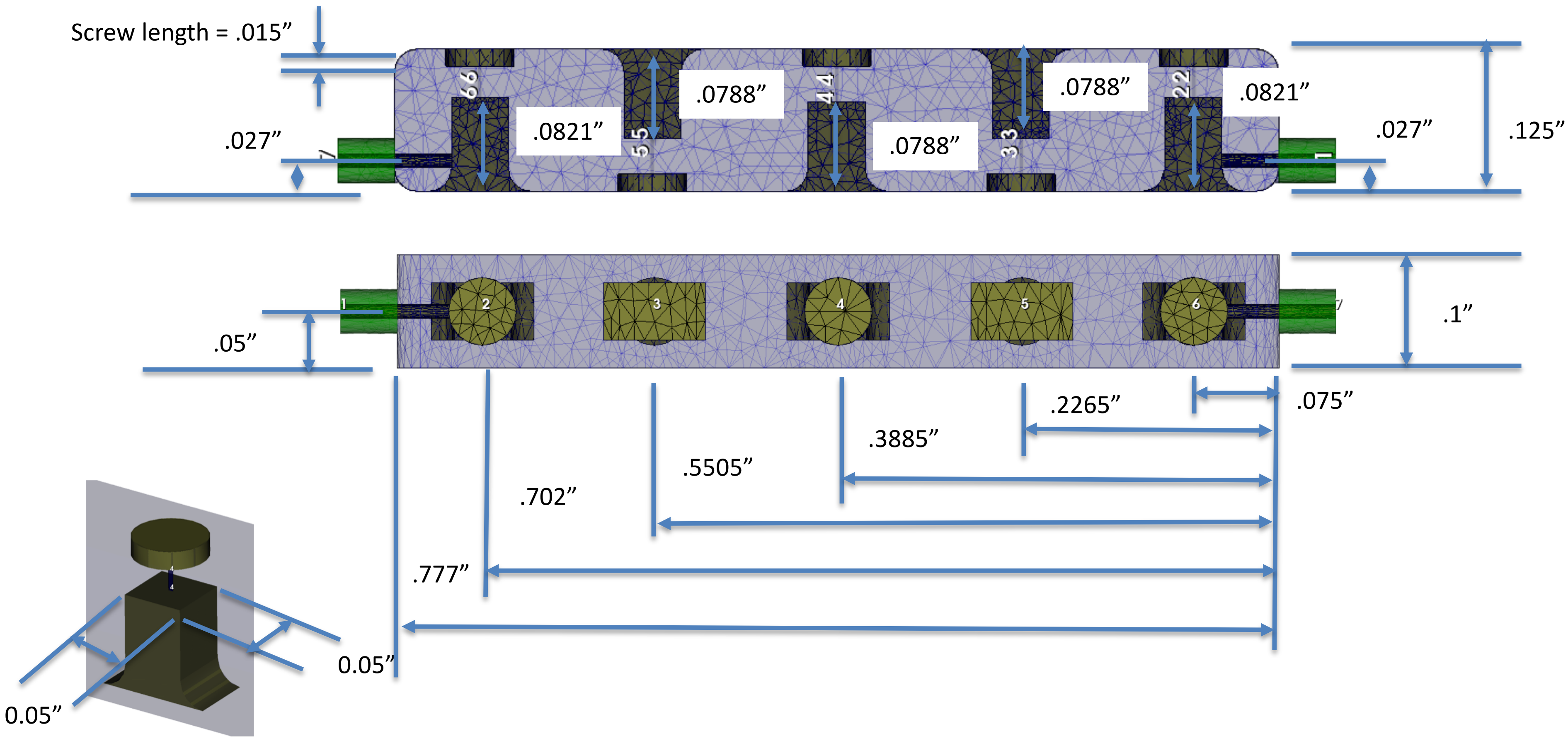




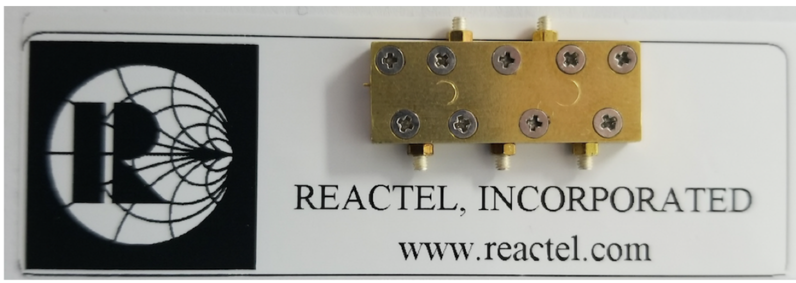
Port Tuning

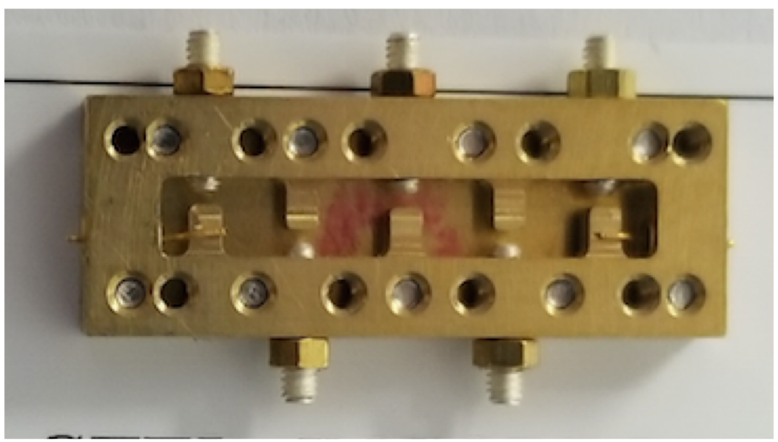
- Optimization is possible using circuit simulator
- Resulting capacitance values reveal the tuning state of the 3D EM model.
- Both positive and negative capacitance values can be used in circuit simulation.
    - **Resonator tuning**: A negative capacitance value indicates that the (EM model) resonator is tuned too low. Positive capacitance represents a resonator that is tuned too high
    - **Coupling tuning**: A positive series capacitance indicates that the coupling was too strong in the EM model (resonators too close)
- Repeat process until the capacitances become sufficiently small.
- Convergence is guaranteed if the changes are not too large.
- Once the resonator sensitivities (kHz per mm) are known tuning becomes very easy.

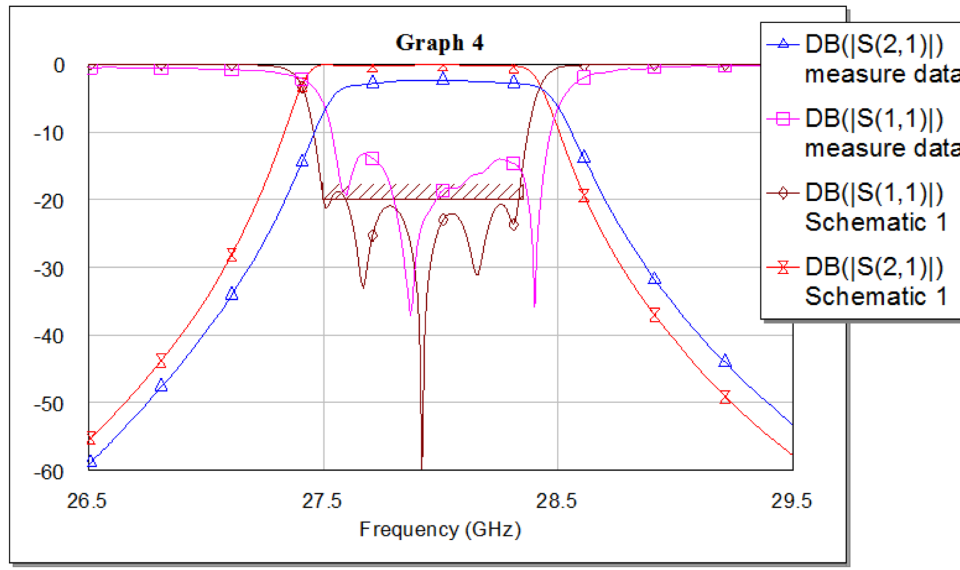
Final Design



Simulated vs. measured results







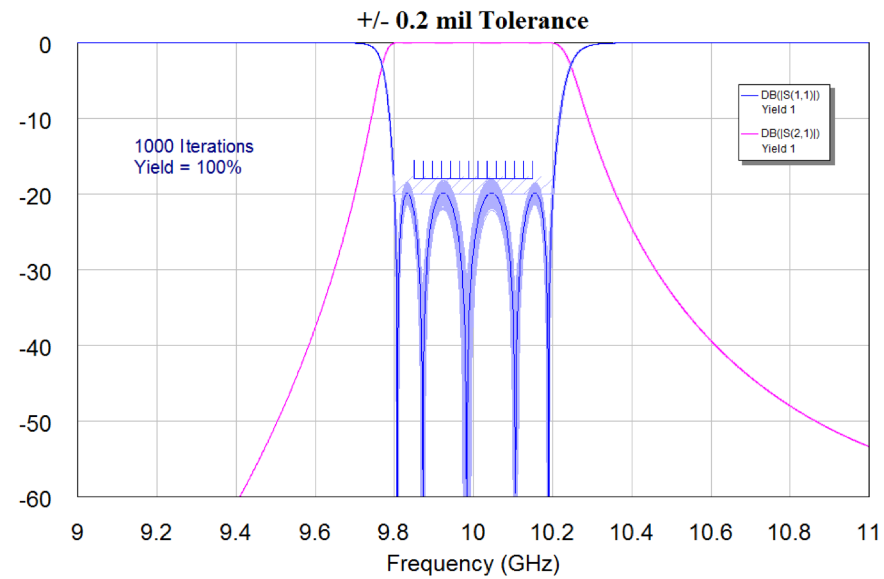
- Simulated vs. measured filter results.
- Cavity filter without silver plating.
- The measured losses will be less once the filter is plated

Manufacturing Tolerances and Yield Analysis

- Modern CNC machine offer 0.0002” tolerances, not including tooling and fixturing
- We can use the relationship between 3D EM model and port tuning capacitors (resonators and coupling) to perform yield analysis using the circuit simulator.
- Physical tolerances from manufacturing process are translated into capacitor tolerances used in yield analysis
- Screw tuning may be inevitable.

Manufacturing Tolerances and Yield Analysis

- Yield analysis of microwave circuits is often done with a Monte Carlo type analysis with a large number of iterations.
- Running these iterations in the EM domain is prohibitive.
- But if the sensitivities we computed convert a capacitance to a physical correction for the EM model, they also imply a length or width change per femto-Farad in the circuit theory domain.



Yield analysis performed on a similar cavity filter using Microwave Office and CST, could also use Analyst

Conclusion

- A practical design method that is independent of filter type/construction has been demonstrated
- Robust equal ripple filter optimization is:
  - A fast and intuitive alternative to design by synthesis
  - A key component for port tuning complex EM based filter models
- EM tools continue to mature and add capabilities/speed, making it practical to include in an optimization loop
- This technique has been used to address the challenge of designing highly sensitive mm-wave filter designs

Acknowledgements

- **Dan Swanson** – DGS Associates (www.dgsboulder.com)
  - Filter Design
  - Dan will be offering a one day workshop, *"Intuitive Microwave Filter Design"*, at the NI office in El Segundo, CA on November 1st
- **Phil Jobson** – Phil Jobson Consulting
  - Parameterization and analyses
- **Jim Assurian**, **Ray Hashemi** – Reactel Corp.
  - Design consulting, manufacturing and test
  - EDI CON 2018 Booth #201
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